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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

ACOUSTIC ISOLATOR FOR DOWNHOLE APPLICATIONS

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CROSS-REFERENCES TO RELATED APPLICATIONS

The present application is a Continuation-in-Part of United States Patent Application Ser. No. 09/583,258 filed on May 31, 2000 that claims priority from and is based upon United States Provisional Patent Application Serial No. 60/137,388 filed on June 3, 1999.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention pertains to logging while drilling apparatus and more particularly to acoustic logging while drilling apparatus and attenuation of acoustic pulses that travel parallel to the direction of drilling.

Related Prior Art

To obtain hydrocarbons such as oil and gas, wells or wellbores are drilled into the ground through hydrocarbon-bearing subsurface formations. Currently, much current drilling activity involves not only vertical wells but also drilling horizontal wells. In drilling, information from the well itself must be obtained. While seismic data has provided information as to the area to drill and approximate depth of a pay zone, the seismic information can be not totally reliable at great depths. To support the data, information is obtained while drilling through logging while drilling or measuring while drilling (MWD) devices. Logging or measuring while drilling has been a procedure in use for many years. This procedure is preferred by drillers because it can be

accomplished without having to stop drilling to log a hole. This is primarily due to the fact that logging an unfinished hole, prior to setting casing if necessary, can lead to washouts, damaging the drilling work that has already been done. This can stall the completion of the well and delay production. Further, this information can be useful while the well is being drilled to make direction changes immediately.

Advances in the MWD measurements and drill bit steering systems placed in the drill string enable drilling of the horizontal boreholes with enhanced efficiency and greater success. Recently, horizontal boreholes, extending several thousand meters ("extended reach" boreholes), have been drilled to access hydrocarbon reserves at reservoir flanks and to develop satellite fields from existing offshore platforms. Even more recently, attempts have been made to drill boreholes corresponding to three-dimensional borehole profiles. Such borehole profiles often include several builds and turns along the drill path. Such three dimensional borehole profiles allow hydrocarbon recovery from multiple formations and allow optimal placement of wellbores in geologically intricate formations.

Hydrocarbon recovery can be maximized by drilling the horizontal and complex wells along optimal locations within the hydrocarbon-producing formations. Crucial to the success of these wells is establishing reliable stratigraphic position control while landing the well into the target formation and properly navigating the drill bit through the formation during drilling. In order to achieve such well profiles, it is important to determine the true location of the drill bit relative to the formation bed boundaries and

boundaries between the various fluids, such as the oil, gas and water. Lack of such information can lead to severe "dogleg" paths along the borehole resulting from hole or drill path corrections to find or to reenter the pay zones. Such well profiles usually limit the horizontal reach and the final well length exposed to the reservoir. Optimization of the borehole location within the formation also can have a substantial impact on maximizing production rates and minimizing gas and water coning problems. Steering efficiency and geological positioning are considered in the industry among the greatest limitations of the current drilling systems for drilling horizontal and complex wells. Availability of relatively precise three-dimensional subsurface seismic maps, location of the drilling assembly relative to the bed boundaries of the formation around the drilling assembly can greatly enhance the chances of drilling boreholes for maximum recovery. Prior art down hole devices lack in providing such information during drilling of the boreholes.

Modern directional drilling systems usually employ a drill string having a drill bit at the bottom that is rotated by a drill motor (commonly referred to as the "mud motor"). A plurality of sensors and MWD devices are placed in close proximity to the drill bit to measure certain drilling, borehole and formation evaluation parameters. Such parameters are then utilized to navigate the drill bit along a desired drill path. Typically, sensors for measuring downhole temperature and pressure, azimuth and inclination measuring devices and a formation resistivity measuring device are employed to determine the drill string and borehole-related parameters. The resistivity measurements are used to determine the presence of hydrocarbons against water around and/or a short distance in

front of the drill bit. Resistivity measurements are most commonly utilized to navigate the drill bit. However, the depth of investigation of the resistivity devices usually extends only two to three meters and resistivity measurements do not provide bed boundary information relative to the downhole subassembly. Furthermore, the location of the resistivity device is determined by some depth measuring apparatus deployed on the surface which has a margin of error frequently greater than the depth of investigation of the resistivity devices. Thus, it is desirable to have a downhole system which can accurately map the bed boundaries around the downhole subassembly so that the drill string may be steered to obtain optimal borehole trajectories.

The relative position uncertainty of the wellbore being drilled and the critical near-wellbore bed boundary or contact is defined by the accuracy of the MWD directional survey tools and the formation dip uncertainty. MWD tools may be deployed to measure the earth's gravity and magnetic field to determine the inclination and azimuth. Knowledge of the course and position of the wellbore depends entirely on these two angles. Under normal conditions, the inclination measurement accuracy is approximately plus or minus two tenths of a degree. Such an error translates into a target location uncertainty of about three meters per one thousand meters along the borehole. Additionally, dip rate variations of several degrees are common. The optimal placement of the borehole is thus very difficult to obtain based on the currently available MWD measurements, particularly in thin pay zones, dipping formations and complex wellbore designs.

Until recently, logging while drilling has been limited to resistivity logs, gamma logs, neutron logs and other non-acoustic logs since acoustic noise caused by drilling and acoustic pulses traveling upstring from the transmitter has presented problems in accurate detection and delineation. These problems cannot be easily isolated by arrival time since the acoustic pulses are generated and detected continuously. Recently, the use of acoustic sensors having a relatively short spacing between the receivers and the transmitter to determine the formation bed boundaries around the downhole subassembly has been used. An essential element in determining the bed boundaries is the determination of the travel time of the reflection acoustic signals from the bed boundaries or other interface anomalies. A prior art proposal has been to utilize estimates of the acoustic velocities obtained from prior seismic data or offset wells. Such acoustic velocities are not very precise because they are estimates of actual formation acoustic velocities. Also, since the depth measurements can be off by several meters from the true depth of the downhole subassembly, it is highly desirable to utilize actual acoustic formation velocities determined downhole during the drilling operations to locate bed boundaries relative to the drill bit location in the wellbore.

Additionally, for acoustic or sonic sensor measurements, the most significant noise source is acoustic signals traveling from the source to the receivers via the metallic tool housing and those traveling through the mud column surrounding the downhole subassembly (tube waves and body waves). In some applications acoustic sensor designs are used to achieve a certain amount of directivity of signals. A transmitter coupling scheme with signal processing method may be used for reducing the effects of the tube

wave and the body waves. Such methods, however, alone do not provide sufficient reduction of the tube and body wave effects, especially due to strong direct coupling of the acoustic signals between the transmitters and their associated receivers.

Some United States patents representative of the current art in determining subsurface formations are as follows.

United States patent number 4,020,452, titled "Apparatus For Use in Investigating Earth Formations", issued to Jean-Claude Trouiller, et al., relates to an apparatus for mechanically filtering acoustic pulses in a well logging tool. This apparatus includes of a substantially rigid member having interruptions in the longitudinal continuity of the member. These interruptions provide tortuous paths for the passage of acoustic energy along the member. A plurality of masses are periodically spaced along the interior of the member and are each mechanically integral with opposite sides of the member at locations chosen to enable the member and masses to cooperate as a mechanical filter. By so doing, the structure made of the member and masses will have good acoustic delay and attenuation characteristics as well as good mechanical characteristics.

United States patent number 5,043,952, titled "Monopole Transmitter For a Sonic Well Tool", issued to David C. Hoyle, et al., relates to a monopole transmitter for a sonic tool which includes an axial tube, a piezoceramic cylinder surrounding the axial tube, an endcap disposed at each end of and firmly contacting the cylinder, and an apparatus for holding the endcaps firmly against the axial tube. The endcaps firmly contact the axial

tube without simultaneously contacting an upper bulkhead. The apparatus may include spring washers disposed between the bulkhead and at least one endcap, or it may include a spring disposed between a nodal mount and each endcap. A nodal mounting tube may be disposed around the axial tube, a ring being disposed at each end of the nodal mounting tube, each ring being disposed outside of the cylinder for biasing the endcaps in tension against a ring thereby holding each endcap firmly in contact against the axial tube.

United States patent number 5,510,582, titled "Acoustic Attenuator, Well Logging Apparatus and Method of Well Logging", issued to James R. Birchak, et al., relates to a sonic well tool for performing acoustic investigations of subsurface geological formations penetrated by a borehole. The well tool generally includes a longitudinally extending body for positioning in the borehole. The tool also includes a transmitter supported by the body for transmitting acoustic energy and a receiver supported by the body for receiving acoustic energy. The tool includes an acoustic attenuation section positioned on the body between the transmitter and the receiver. This section includes one or more cavities defined by the body, inertial mass members positioned inside the cavities in a suitable manner to form a gap between the wall of the cavity and the inertial mass members, and an acoustical attenuation fluid in the gap. The method for attenuating sonic waves generally includes transmitting a sonic wave from the transmitter to the tool, passing the sonic wave through the acoustic attenuation section, and receiving attenuated wave at the receivers.

United States patent number 5,036,945, titled "Sonic Well Tool Transmitter Receiver Array Including an Attenuation and Delay Apparatus", issued to David C. Hoyle, et al., relates to a sonic well tool that includes a transmitter array having at least one monopole transmitter and at least one dipole transmitter and a receiver array for receiving sonic pressure wave signals from a surrounding borehole formation. A first attenuation and delay apparatus is positioned above the receiver array and a second attenuation and delay apparatus is positioned below the receiver array in the sonic well tool. The first attenuation and delay apparatus includes an attenuation member comprising a plurality of interleaved rubber and metal like washers for attenuating compressional and flexural waves propagating along a metal center support rod to the receiver array and an inner housing comprising a bellows section having a corrugated shape and a thin transverse dimension for delaying the propagation of compressional and flexural waves along the inner housing to the receiver array. The second attenuation and delay apparatus includes a plurality of mass loading rings surrounding the outer housing of the sonic well tool for attenuating the flexural waves propagating up the outer housing from a sonic transmitter ad a further inner housing including a further bellows section having a corrugated shape and a thin transverse dimension for delaying the propagation of compressional and flexural waves up the tool, along the inner housing, to the receiver array. The sonic well tool also includes a differential volume compensator for changing the quantity of oil encapsulated in the sonic well tool in accordance with changes in oil volume and changes in borehole temperature and pressure. The receiver array includes a plurality of hydrophone sets, each hydrophone set including at least one pair and preferably two pair of hydrophones disposed in a cross section of the tool, one

hydrophone of a pair being disposed opposite the other hydrophone of the pair in the cross section.

United States Patent Application Ser. No. 09/201,988, now United States Patent 6,082,484 to *Molz & Dubinsky,* having the same assignee as the present invention discloses the use of a section of a drill collar that has a plurality of shaped cavities filled with oil. The passage of an acoustic wave sets up a resonance of the fluid in the shaped cavity. The frequency of resonance depends upon the shape and size of the cavity and the properties of the fluid in the cavity. In one embodiment of the invention, the cavities are spherical. Another embodiment of the invention uses cylindrical cavities with a piston restrained by a spring within the cavity. Changing the spring constant provides additional control over the frequencies that are attenuated. The '988 application also discloses the use of segmented isolators in which the drill collar section is filled with layers of a composite material in which the layers have a different density. The thicknesses of the individual layers is selected to attenuate certain frequencies.

United States Patent Application Ser. No. 09/583,258 to *Egerev et al*, having the same assignee as the present application and the contents of which are incorporated herein by reference, discloses a system and method for attenuation of acoustic waves that travel through a drill collar in a logging while drilling operation. The system includes a plurality of heavy masses attached to an inner wall of the drill collar. The heavy masses constitute mass discontinuities that attenuate waves traveling through the drill collar. In one embodiment of the invention, the mass discontinuities are rings and attachment is done by neck pieces. These neck pieces extend out from the outer circumference of the

rings and may be an original outer circumference of the ring that has been milled down by cutting out portions of the ring. This allows significantly less than the entire outer circumference of the hanging rings to be in contact with the inner surface of the drill collar. Thus, the rings will more efficiently attenuate the vibrational force of the acoustic pulses coming in contact with the hanging ring. The plurality of heavy hanging rings are spaced and sized for the maximum attenuation of acoustic pulses in a predetermined range, preferably in the range of 10 khz to 20 khz. The system may include steel rings as the plurality of heavy hanging rings. In an alternate embodiment, the plurality of heavy hanging rings may be a heavier, more dense material such as tungsten. The plurality may have as many as ten rings or as few as six, with eight being another possibility. The spacing of the rings may vary between twelve and fourteen centimeters, depending on the material used. In a still further embodiment, a pipe may be placed within the inner circumference of the rings to isolate the attenuation rings from the flow of drilling mud. The isolation pipe may be of any material, however, a material that is non-rigid that is less likely to conduct vibrational forces is preferred. In another embodiment of the invention, the mass discontinuities are attached to the drill collar over a substantial portion of their individual axial lengths. Such an arrangement acts as a low pass filter. When this mechanical arrangement is used with an electrical bandpass filter in the tool, high frequencies are efficiently attenuated. In yet another embodiment of the invention, the attenuator section comprises a cylindrical body with sections of different inside and/or outside diameters to produce a ringed pipe: the sections of different diameter each have a characteristic passband and a reject band for attenuation of signals.

The attenuator system of Egerev is expensive to fabricate and difficult to maintain

due to the multiple mass discontinuities incorporated on the inner wall of a drill collar. The erosive flow of drilling fluid in the inside of the collar can cause severe damage to the isolators absent an internal sleeve. It would be desirable to have an attenuator system that is less expensive to fabricate and easier to maintain.

Summary of the Invention

The present invention provides a system and method for attenuation of acoustic waves that travel through a drill collar in a logging while drilling operation. The system includes a plurality of heavy masses attached to an outer wall of the drill collar. The heavy masses constitute mass discontinuities that attenuate waves traveling through the drill collar. In one embodiment of the invention, the mass discontinuities are rings and attachment is done by neck pieces. These neck pieces extend in from the inner circumference of the rings. This allows significantly less than the entire inner circumference of the rings to be in contact with the outer surface of the drill collar. Thus, the rings will more efficiently attenuate the vibrational force of the acoustic pulses coming in contact with the ring. The plurality of heavy rings are spaced and sized for the maximum attenuation of acoustic pulses in a predetermined range, preferably in the range of 10 khz to 20 khz. The system may include steel rings as the plurality of heavy rings. In an alternate embodiment, the plurality of heavy rings may be a heavier, more dense material such as tungsten. The plurality may have as many as ten rings or as few as six. The spacing of the rings may vary between twelve and fourteen centimeters, depending on the material used. In another embodiment of the invention, the mass discontinuities

are attached to the drill collar over a substantial portion of their individual axial lengths. Such an arrangement acts as a low pass filter. When this mechanical arrangement is used with an electrical bandpass filter in the tool, high frequencies are efficiently attenuated.

In another preferred embodiment, a system for preferential attenuation comprises a plurality of spaced-apart masses asymmetrically attached to an adjacent outer wall of the collar.

Brief Description of The Drawings

For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

Figure 1 is an illustration of a drill system having a measuring while drilling device mounted in the drilling apparatus;

Figure 2 illustrates raypaths of acoustic signals between the transmitter and the receiver;

Figure 3 is an illustration of an attenuation system for use on a well drilling collar;

Figure 4 is a graphical representation illustrating the effects of an increased

number of attenuation elements of a system as that illustrated in **Figure 1**;

Figure 5 is a graphical representation illustrating the effects of increasing the weight of attenuation elements of a system as that illustrated in **Figure 1**.;

Figure 6 is a graphical representation illustrating the attenuation effect of the system of **Figure 1**;

Figures 7a and **7b** show a comparison of the invention of **Fig. 2** with one in which the mass discontinuities are attached to the drill collar over a substantial length;

Figures 8a - 8c show alternate embodiments of the invention in which attenuation is accomplished by means of recesses that produce mass discontinuities in a body of the attenuator;

Figure 9 shows a comparison of frequency spectra of attenuators having different types of recesses having a fixed length;

Fig. 10 shows alternate embodiments of the invention in which the diameter of the attenuation sections is varied;

Figs. 11 shows an alternate preferred embodiment using an arrangement of mass bodies attached to an external wall of a drill collar; and

Fig. 12 shows an asymmetrical arrangement for a mass ring attached to an external wall of a drill collar.

<u>Description of the Preferred Embodiment</u>

The present invention provides a system and method for attenuating acoustic waves in a down hole tool that is being used to obtain information about subsurface formations, some of which are believed to be holding hydrocarbon deposits. **FIG. 1** is a

schematic illustration of the use of a Measurement-While-Drilling (MWD) apparatus while drilling a well. At the surface of the earth **5** a drilling rig **1** is used to drill a borehole **23** through subterranean formations **25a, 25b, 25c** etc. Those versed in the art would know that a drillship or a platform could be used to drill a borehole into subterranean formations covered by a body of water. A drilling tubular **13**, that could be made of drill pipes or coiled tubing is used to rotate a drillbit **17** at the bottom, the rotating action of the drillbit and axial pressure carving out the borehole. When coiled tubing is used for the drilling tubular, a drilling motor (not shown) is used to impart the necessary rotary motion to the drillbit.

A variety of transducers are used downhole in a sensor assembly **11.** This sensor assembly makes measurements of properties of the formations through which the borehole is being drilled. These could include electromagnetic, gamma ray, density, nuclear-magnetic resonance, and acoustic sensors. For illustrative purposes only, an acoustic transmitter array **31** and an acoustic receiver array **33** are indicated. Those versed in the art would recognize that other configurations of the acoustic transmitters and receivers could be used.

Turning now to **FIG. 2,** the transmitter **31** and the receiver **33** are shown inside the borehole **23**. The annulus between the drilling tubular **13** and the borehole **23** is filled with a drilling fluid. The fluid is conveyed down the borehole inside the drilling tubular to the drillbit and returns up the hole via the annulus. Excitation of the transmitter produces acoustic signals. A portion of the signal, denoted by the raypath **43**, is referred to as the direct arrival and travels through the tool to the receiver. The transmitter also

produces an acoustic signal in the borehole fluid that enters into the formation. One portion of it, illustrated by the raypath **41** travels as a body wave through the formation and carries information about the formation that it traverses. The receiver also detects other signals, such as tube waves that involve a coupled wave between the fluid and the formation, Stoneley waves that are surface waves in the fluid, and signals reflected from acoustic reflectors within the formation.

In an MWD tool, as in wireline tools, the body wave **41** through the formation usually arrives before the tube wave and the Stoneley wave. However, in an MWD tool, the direct arrival **43** through the tool commonly arrives before the desired signal component **41** that carries information about the acoustic properties of the formation. In addition, the drillbit **17** itself is continuously generating acoustic signals traveling through the drilling tubular **13**. Consequently, it becomes very difficult to determine a travel time for the formation body wave **41.**

In order to attenuate the direct arrival **43,** the tool a pulse attenuator **40** is located in tool **11** between transmitter **31** and an receiver **33**. Only one transmitter and receiver are illustrated for demonstration. In practice, there may be several receivers and transmitters and the present invention operates with any arrangement, the only requirement is that attenuator **40** be located between the transmitter and the receiver.

In one embodiment of the invention, the acoustic isolator is based upon an array of mass rings attached to the inner wall of the drilling collar. Such an array presents an

interference filter providing a stop band at a predetermined frequency for longitudinal sound waves propagating along the walls of a collar. The device exhibits sufficient damping within the predetermined frequency range as well as good mechanical strength. The efficiency of an isolator of this type increases proportionally to the number of the rings N as well as to the ratio M / μ, where M is the mass of a single ring, μ is a mass per unit length of the collar. Hence, the efficiency of the isolator is very sensitive to even minor changes in outer dimensions of the pipe as well as to the changes in demands to its wall thickness.

The attenuation provided by the isolator section is designed to be minus forty decibels within the frequency range of twelve through eighteen kilohertz. The isolator design satisfy the mechanical requirements specified concerning the limitations on inner diameter, outer diameter, minimal cross section area and others.

Figure 3 is a partial illustration of an attenuation system **50** for a sound tool (not shown) in a drill collar **52** using an array of hanging mass irregularities **54, 56, 58** ... (may include up to ten elements) mounted on inner wall **60** of drill collar **52**. Mass irregularities **54, 56, 58,** ... are secured to inner wall **60** by neck pieces **62** which extend out from outer circumference **64, 66, 68,** ... of mass irregularities **54, 56, 58,** ... respectively. Neck pieces **62** are smaller both in depth and width than outer circumferences **64, 66, 68,** ... of mass irregularities **54, 56, 58,** ... so that mass irregularities **54, 56, 58,** ... are held firmly against inner wall **60**, but not so firmly that acoustic pulses traveling through drill collar **52** are transferred without attenuation. In

this manner, mass irregularities **54, 56, 58,** ... are held firmly but not tightly.

In an alternate embodiment, an inner pipe **64** may be provided to protect array of mass irregularities **54, 56, 58,** ... from mud flow. Inner pipe may be of any material to isolate mass irregularities **54, 56, 58** ... from the mud flow, however, a material that is non-rigid and has a degree of flexibility is preferred. A material that is less likely to transfer acoustic pulses toward the receivers is desired.

The operation of the attenuation filter may be understood by the following discussion. The attenuator section has N mass irregularities or elements, each element having the shape of rings or donuts attached to the inner surface of a pipe at the points $x = x_j$, (where $j = 1,\ldots n$). The origin of coordinates coincides with the first irregularity, i.e. $x_0 = 0$. The mass of a ring j is m_j. The distance between two neighboring elements is:

$$l_j = x_{j+1} - x_j.$$

At $x > x_n$, an incident longitudinal sound wave of a unit amplitude traveling towards the origin of coordinates may be denoted by

$$pe^{-i\left[k\left(x-x_n\right)-\omega t\right]}$$

where

$k = \omega/c$ is a wavelength constant,

$\omega = 2\pi f$ is an angular frequency,

c = the velocity of sound.

Due to the presence of an array there exists (at $x > x_n$) a reflected wave $p_r = V_n(\omega)e^{ik(x-xn)-i\,\omega t}$, where $V_n(\omega)$ is a reflection coefficient for an array of n irregularities. In the present invention, the dimensions of irregularities are small as compared with the wave length at a given frequency $\omega = 2\pi/k$. The density ρ as well as linear mass of a pipe μ are also of great importance in the attenuation. In the present invention, the mass m_j is much greater than $\mu\, h_j$, where h_j is the length of attachment zone for the mass m_j. Such an array presents an interference filter providing a stop band at a predetermined frequency range for longitudinal sound waves propagating in the walls of a pipe. .

In the solution of a wave equation, the length of a contact zone, Δl, between a ring and an inner wall of a pipe is small as compared to the wavelength of interest λ. Under these circumstances the propagation of the longitudinal wave can be described by the following differential equation:

$$YS\frac{\partial^2 u}{\partial x^2} - \mu\frac{\partial^2 u}{\partial t^2} - M_j\frac{\partial u^2}{\partial t^2}\delta\left(x - x_j\right) = 0$$

(1)

Where:

Y is the Young's modulus of the pipe material,

S is the cross section area of the pipe wall,

u is the displacement,

μ is the linear mass of the pipe, and

x is the longitudinal coordinate.

When considering propagation of a sinusoidal wave, the displacement u may be represented by a function of the form $u(x)exp(-i\omega t)$, where, ω is the angular frequency, The differential wave equation then takes the form:

$$YS\frac{\partial^2 u}{\partial x^2} + \mu\omega^2 u + M_j\omega^2 u\delta(x - x_j) = 0 \qquad (2)$$

For an array of N mass irregularities, the solution takes the form

$$u(x) = Ae^{ikx} - \sum_{j=1}^{N} b_j G(x - x_j)u(x_j) \qquad (3)$$

where,

A is an initial wave amplitude,

$G(x - x_j) = exp\ (ix.\ x - x_{j.})\ /\ (2\ y\ s\ k)$ is Green function, and

$b_j = M_j\ \omega$ is the magnitude of an irregularity.

Hence the transmission coefficient at a position x that is greater than x_n can be found as: T = u (**x**) / A, which may be expressed in decibels using the usual conversion factor.

The transmission coefficient of the array may also be obtained by other methods. One such method is an impedance approach, the relative input impedance is given by the formula:

$$Z_{in} = (p/v\rho c)$$

where:

p = pressure,

c = velocity of sound in the medium,

v = vibrational velocity, and

ρ = density.

For an array of N elements, the impedance is calculated with the help of the following recurrence procedure:

$$Z_{in}^{j+1} = \frac{Z_{in}^{j} - i\tan\left(kl_j\right)}{1 - iZ_{\varepsilon}^{j}\tan\left(kl_j\right)} - i\frac{km_j}{\mu} \quad , j = 1,2,\ldots N$$

Figures 4 and **5** illustrate plots of transmission vs. frequency. The influence of the number of elements is illustrated in **Figure 4**. Transmission curves are shown for six elements, eight elements and ten elements. The increase in the number of elements only slightly changes the transmission curve at the borders of the predetermined frequency band. However, the attenuation values of the transmission curves in the middle of the frequency band are greatly affected. The period of an array l is important to place the

transmission curves at the proper frequency. In the preferred embodiment an optimal value for the spacing between elements is 5.12 inches or approximately thirteen centimeters for the inner and outer diameter used. However, other spacings such as fourteen or twelve centimeters may also be used and provide acceptable results. The influence of the mass of a single element is illustrated in **Figure 5**.

Figure 4 illustrates attenuation curves for arrays of ten elements. Each curve is for elements of different weights. A first curve is for ten elements, each weighing eight kilograms, the second for elements weighing eleven kilograms and a third for elements weighing fourteen kilograms. An increase in the mass M results in changing the low frequency border. The high frequency border remains essentially unchanged. All the transmission curves show that transmission loss exceeds forty decibels within the predetermined frequency band between twelve and eighteen kilohertz.

The calculations were performed for an array of N identical equally spaced irregularities. Transmission coefficient was calculated vs. frequency within the frequency range from five to twenty kilohertz.

Figure 6 is a graphical representation of the attenuation of a preferred embodiment of the present invention. In the preferred embodiment, ten elements were used with a spacing of thirteen centimeters between elements. Rings of stainless steel were used as mass irregularities **54, 56, 58** .... It can be seen that the arrangement of the preferred embodiment provides attenuation of waves in the range of eight to eighteen

kilohertz. By using his system, interference of waves traveling through the collar of a drilling tool can be greatly reduced and acoustic logging is possible during a drilling operation.

Figs 7a and **7b** show a comparison between the embodiment discussed above with respect to **Fig. 2** and an alternate embodiment of the invention using a different arrangement of attaching the mass discontinuities to the drill collar. Shown in the upper portion of **Fig. 7a** is a drill collar **152a** to which a mass **154a** is attached by means of a neck **158a**. This corresponds to the arrangement discussed above with reference to **Fig. 2.** Shown in the upper portion of **Fig. 7b** is an alternate arrangement in which a mass **154b** is attached to the drill collar **152b** over substantially the full length of the mass. Shown in the lower portion of **Fig. 7a** is a schematic representation of the effective mass discontinuity **170a** as seen by a propagating wave: typically, such a mass discontinuity provides approximately 6 to 8 dB of attenuation of the wave. The lower portion of **Fig. 7b** shows the effective mass discontinuity **170b** as seen be a propagating wave: effectively, an attenuation of 2 - 3 dB of attenuation is provided at each boundary. By an analysis such as discussed above with respect to equations 1 - 4, the arrangement of **Fig. 7b** is shown to act as a low pass filter. By suitable choice of the spacing and size of the weights, the effective cutoff frequency can be made to be around 10 kHz. When used in combination with an electrical bandpass filter (not shown) on the tool, body waves through the drill collar may be effectively attenuated.

Figs. 8a - 8c show alternate embodiments of the invention in which the isolator

comprises a machined cylindrical member. In **Fig. 8a**, the cylindrical member has an outer diameter of **OD** and an inner diameter of **ID**. The inner diameter allows passage of drilling mud. The inside wall if the cylindrical member has recess of length **L** therein. A body wave encounters regions of different cross sectional areas and mass densities, similar to the embodiments discussed above, resulting in attenuation of body waves.

Fig. 8b shows an arrangement in which the recess are on the outside of the isolator whole **Fig. 8c** shows an arrangement in which there are recess on both the outside and the inside of the isolator.

Fig. 9 shows the results of a finite element ("FE") simulation of the various embodiments shown in **Figs. 8a - 8c**. The abscissa is the frequency and the ordinate is the normalized amplitude of waves passed by the attenuator. Note that the amplitude scale is linear, rather than being in decibels. The curve **301** shows the spectrum for a cylindrical pipe. The curve **303** shows the spectrum for cuts on the inside of the pipe, **305** is for recesses on the inside and outside of the pipe while **307** is for recesses on the outside of the pipe. Similar FE simulations have been carried out for various lengths **L** of the recesses. Based upon these simulations, for an OD of 7.09", in a preferred embodiment of the invention, a value of **L** of 3.15" (8.5cm) with recesses on both the inside and the outside of the isolator is used.

The results in **Fig. 9** are for a plurality of equally spaced recesses having the same length and the same depth of the recesses. Other embodiments of the invention use a

combinations of sections having different lengths and different depths of inner and outer recesses. Examples are shown in **Fig. 10**. Each section **400** may be considered to be a waveguide with an associated pass-band and a reject band determined by the inner diameter **403** and the outer diameter **401**. As may be seen in **Fig. 10**, each section has an axis parallel to the longitudinal axis **405** of the body of the attenuator. By using such a combination of different inner and outer diameters , a broad range of frequencies may be attenuated. This attenuation is in addition to the attenuation produced by reflections between adjacent sections **400**. In the presence of borehole fluid on the inside and outside of the sections, the waveguides are "leaky" waveguides that allow energy to propagate into the fluid. In a preferred embodiment of the invention, the inner diameters range from 2" to 6" and the outer diameter ranges from 4" to 10".

Figs. 11 and 12 show an alternate preferred embodiment using an arrangement of mass bodies attached to an external wall of a drill collar. The effects are similar to those discussed above in reference to **Figs. 7a** and **7b**, however the external arrangement offers advantages of easier and less expensive fabrication and easier maintenance than masses connected to the internal wall of the drill collar as described previously. The mass discontinuities shown in **Figs. 11** and **12** are essentially cylindrical rings. The rings may be made of steel or,alternatively, may be made of a more dense material such as tungsten. In **Fig. 11**, the mass rings **505a** and **505b** have an internal diameter **501** which is greater than the external diameter **503** of the drill collar **504** and are attached to the drill collar **504** by necks **506a** and **506b**, respectively. As with the mass discontinuity described previously in **Fig. 7a**, such a mass discontinuity as shown in **Fig. 11** provides

approximately 6-8 dB of attenuation of a direct acoustic wave traveling in the drill collar **504**. Note that for simplicity, only two rings are shown in each of **Fig. 11** and **Fig. 12**, however the number of rings will typically be between 6 and 10 with a spacing between approximately 12 and 14 cm. for a frequency range of interest of 10 khz to 20 khz. Note that this is an exemplary range and that other frequency ranges may be filtered by the appropriate selection of mass size, number and spacing as previously described. An advantage of the external arrangement can be realized because attenuation is related to the mass of each ring **506a, 506b,** divided by the mass per unit length of the drill collar, as previously discussed. For example, for similar spacing and length of the rings as described in **Fig. 7a,** the external rings **506a, 506b** can have a smaller thickness t due to the d^2 effect on ring volume. Because the rings **506a,506b** are at a larger diameter than the internal ring described in **Fig. 7a**, if the length of the rings is the same, rings **506a, 506b** will be thinner to have the same mass for the same material. Alternatively, if the ring thickness t and the length are held the same as before, then the mass of rings **506a, 506b** would be greater than the mass of the ring of **Fig. 7a**. The increased mass will result in increased attenuation for the configuration of **Fig. 11** as compared to the configuration of **Fig. 7a**.

Fig. 12 shows an asymmetrical arrangement for a mass ring attached to a collar. Exemplary mass rings **605a, 605b** are coupled to collar **604** at shoulder **607** having a raised diameter **606**. The masses **605a, 605b** contact the collar over a portion K of the length L of the masses **605a, 605b** such that the masses are supported over a portion of their length and cantilevered for a portion of their length. The masses may be attached by welding, brazing, press fitting, shrink fitting or any other suitable technique. For

exemplary purposes, the number of masses and the spacing of the masses are essentially the same as for those described for **Fig. 11**. The acoustic source is located in the direction of the supported portion of the masses **605a, 605b**, typically an uphole direction, as shown in **Fig. 12**. As acoustic waves from the source travel toward the receiver, or downhole, they encounter a geometry which allows the acoustic wave to enter the masses **605a, 605b** and be essentially trapped in the cantilevered section. Waves traveling in the opposite direction do not encounter the same geometry but essentially see only the supported section of masses **605a, 605b** and are not attenuated as much as downward travelling waves. The arrangement shown in **Fig. 12** is preferred for a drilling operation because it provides increased support area for the masses as compared to that of **Fig. 11,** thereby providing increased stability of the masses as they encounter the significant wall forces involved in downhole drilling. The external arrangement of the masses of **Fig. 11** and **Fig. 12** provide improved cleaning, inspection, and maintenance compared to the internal mass arrangements described previously. While the masses shown in **Fig. 11** and **Fig. 12** have sharp corners, radiused corners may be provided for stress relief and/or to facilitate ease of manufacturing. Such techniques are known in the art and are not described further.

While there has been illustrated and described a particular embodiment of the present invention, it will be appreciated that numerous changes and modifications will occur to those skilled in the art, and it is intended in the appended claims to cover all those changes and modifications which fall within the true spirit and scope of the present invention.